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Recent advances in dendroclimatology in China

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ABSTRACT

Considerable progress has been made in dendroclimatological research in China during the period 2000–2017, including a significant increase in the spatial coverage of tree-ring chronologies developed for paleoclimatic research. New tree-ring sampling sites have been established across the Tibetan Plateau, as well as the north-eastern and sub-tropical eastern parts of China. Most of the studies use coniferous trees, although different plant functional types (e.g., broadleaf species and shrubs) have also been increasingly investigated. Tree-ring chronologies longer than 600 years, however, are mostly found on the Tibetan Plateau, with the longest one extending back to 2637 BCE (before Common Era). Most tree-ring records in the eastern parts of China are < 400 years long. Tree-ring width is the most commonly studied parameter, although stable isotope ratios and wood density data have also been obtained for specific sites. Stable oxygen isotope data frequently shares a common hydroclimate signal, whereas the climate or environmental signals remain inconsistent for the few available stable carbon isotope records. In general, tree-ring width-based temperature reconstructions originate from higher elevation sites (i.e., treeline) compared to hydroclimate reconstructions. Precipitation or drought reconstructions are mainly obtained from regions with an annual precipitation of < 800 mm. Most of the tree-ring reconstructions are based on individual site or local-scale chronologies, although a limited number of regional-scale and field reconstructions have been produced. The most prominent identified characteristics of the recent advances in dendroclimatological research for China have manifested in aspects such as an expanded network of sampling sites, improved climate reconstruction methodology, and improved uncertainty estimations in the latter. Furthermore, the traditional statistical-based tree growth–climate relationships have been supplemented by monitoring and modeling approaches. Based on the progress from 2000 to 2017, and on the research potential of the country in this field, we expect additional widening of the dendroclimatological investigations in China during the coming years.

1. Introduction

Dendrochronology is the discipline of dating tree-rings to the calendar year of their formation (Fritts, 1976). With accurately dated tree-rings, it is possible to detect climate and/or environmental signals that are common within a population of trees (Schweingruber, 1988; Cook and Kairiukstis, 1990; Hughes, 2002; Cook and Pederson, 2011; Büntgen et al., 2018a). Annual resolution and precise dating control, in combination with a large spatial distribution of trees and the effectiveness of simple statistical models between tree-ring growth

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parameters and climate data, make trees one of the most used proxy archives for paleoclimate studies (e.g., Christiansen and Ljungqvist, 2012; Ljungqvist et al., 2012; Schneider et al., 2015; Stoffel et al., 2015; Wilson et al., 2016; Esper et al., 2016; Anchukaitis et al., 2017). Hundreds to thousands of years of climate or environmental information have been extracted from tree-ring chronologies in different environments across most of the world (Cook et al., 2004, 2010, 2015; PAGES2k Consortium, 2013; Hellmann et al., 2016; Luterbacher et al., 2016; Esper et al., 2016, 2018). Such long climate reconstructions can provide a baseline for placing current climate changes in a long-term context, for evaluating the performance of climate model simulations, and for distinguishing anthropogenic fingerprints from natural climate dynamics (e.g., Fernández-Donado et al., 2013; PAGES2k–PMIP3 Group, 2015; Ljungqvist et al., 2016).

In China, the first dendroclimatological studies were conducted in the 1930s and 1940s (e.g., Zheng, 1935; Deng, 1948). The first tree-ring laboratory in China was established at the Institute of Geography of the Chinese Academy of Sciences in Beijing (Wu and Zhan, 1991). The achievements in early Chinese dendroclimatology, prior to 1991, were synthesized by Wu and Zhan (1991). Subsequent dendroclimatological work was conducted on the Tibetan Plateau (TP) (e.g., Bräuning, 1994, 1999) and north-central China (e.g., Hughes et al., 1994) during the 1990s. Dendroclimatological research in China has undergone rapid development thereafter, with the improvement of technology, and the emergence and application of new methods.

In this review article, we aim to synthesize the advances of dendroclimatological research in China during the period 2000–2017. In the results and discussion, we synthesize (1) the expansion of the studied regions and tree species in China, (2) the evolvement of the increasing number of studied tree-ring parameters, (3) the increasing temporal length of available chronologies and the application of more advanced detrending methods, (4) the characteristics of the chronologies, (5) the current state of available dendroclimatological reconstructions, and (6) the new monitoring and modeling approaches associated with dendroclimatology in China. We conclude by discussing future prospects and research topics of dendroclimatology in China for the coming years.

2. Materials and methods

For the purpose of this study, we collected and assessed the scientific articles published in English in the international journals, involving tree-ring data sampled within the national borders of China. As a selection criterion, each article should include at least one tree-ring chronology and analyze the relationship(s) with instrumental climate data. For some articles providing composite chronologies assembled from previously published individual study sites, the original study was not included to avoid duplication. Using the key words “tree-ring”, “climate” and “China”, we obtained > 15,000 entries from Google Scholar for the period 2000–2017. However, after checking each hit individually, we found that only a small fraction of 143 articles actually matched our selection criteria. In addition to the search using Google Scholar, articles were collected from the webpages of individual dendroclimatologists. We also screened tree-ring data deposited in the International Tree-Ring Data Bank (ITRDB; Grissino-Mayer and Fritts, 1997). Using this combined search approach, a total of 282 relevant articles were identified. Studies involving field reconstructions, monitoring and modeling associated with dendroclimatology were additionally collected, but were not included in the total number of articles mentioned above.

In addition to the bibliographic data, we documented the characteristics of all published dendrochronological records included in our assessment, and their relationships with climate or environmental data. The listed parameters contain information about site location (e.g., coordinates, elevation) and tree species, the studied tree-ring parameters (e.g., ring width, wood density or stable isotope variations), the type of collected wood material (living or dead trees, or/and archaeological wood), the detrending method used to derive the final chronologies, and related statistics, including reliable start and end years (i.e., an expressed population signal [EPS] or subsample signal strength [SSS] threshold value of 0.85; Wigley et al., 1984), mean sensitivity (an index of relative inter-annual variability of tree-ring chronologies), and average correlation coefficients between trees (Rbar; Fritts, 1976). Then, we provided information about the detected climate signal(s) (herein we refer to the chronologies that were used to conduct climate reconstructions; while articles lacking climate reconstruction were not considered in our analyses), correlation coefficients (between dendrochronology and the detected climate signals) and climate reconstruction quality. Articles that did not document any detailed values of the parameters mentioned above or the applied methods (marked as “NaN” in the Supplementary Material) were not included in our assessment. If the same study site was re-examined by the same author(s) or the same research group, it was included only one time in our analysis. To demonstrate the abundance of the dendroclimatological work conducted in China to date, each sampling site was recorded based on the coordinates presented by the original authors, even if these were combined to establish one composite tree-ring chronology. To avoid arbitrariness, we included some specific examples to show the progress based on either one of three criteria: (1) pioneering work in a specific field, (2) new techniques or approaches introduced, or (3) high impact of the published articles (as measured from the Journal Citation Reports of Thomson Reuters Web of Science). Given the great amount and richness of dendroclimatological investigations conducted in China, this overview is somewhat selective and condensed.

3. Results and discussion

3.1. Study regions and species

Only 35 tree-ring sampling sites existed in China prior to 1991 (Fig. 1a), mainly from the mountain regions of northwestern China and the southern TP, as well as from cold-temperate regions in the north. To our knowledge, the number of sites had increased to 729 by the end of 2017. The number of published tree-ring records, as well as the accumulated impact factor of the published articles, has steadily increased from 2000 to 2017 (Fig. 1b). The greatest coverage of dendrochronological records is available for the eastern parts of the TP (Fig. 1c), where forest ecosystems are located as shown by land cover data in China (Ran et al., 2012; herein we only differentiated forested and unforested areas for an easier comparison). Extensive data collections have additionally been carried out for the northwestern, northeastern, and sub-tropical eastern parts of China. Apparently, tree-ring sites are located not only in traditional sampling environments, e.g., near the altitude or latitude tree-lines or in arid and semiarid areas (Fritts, 1976; Schweingruber, 1988; Cook and Kairiukstis, 1990; St. George, 2014; Hellmann et al., 2016; Büntgen et al., 2018a; Seftigen et al., 2018) but also in areas characterized by a warm and wet climate, such as the sub-tropical regions of southeastern China (e.g., Duan et al., 2013; Shi et al., 2013; Cai and Liu, 2017).

The majority of the studied species are coniferous taxa, in particular belonging to the genus *Picea* (26%), *Juniperus* (22%), *Pinus* (22%), *Larix* (12%) and *Abies* (8%). Other studied tree species include *Tsuga dumosa* (0.5%), *Tsuga longibracteata* (0.2%), *Betula ermanii* (0.2%). Other species are present, but in very low numbers. For example, the growth pattern of *Populus euphratica* as well as its possible relationships with climate or environmental data has been investigated in arid riparian forests (e.g., Liu et al., 2007; Zhang et al., 2012; Liang et al., 2013; Peng et al., 2017). Furthermore, a small number of shrub species have been studied using traditional dendrochronological methods, such as *Tamarix ramosissima* (Xiao et al., 2005), *Rhododendron nivale* (Liang and Eckstein, 2009), *Juniperus pingii* var. wilsonii (Liang et al., 2012), and *Cassiope fastigiata* (Liang et al., 2015). In particular, a 400-year-old

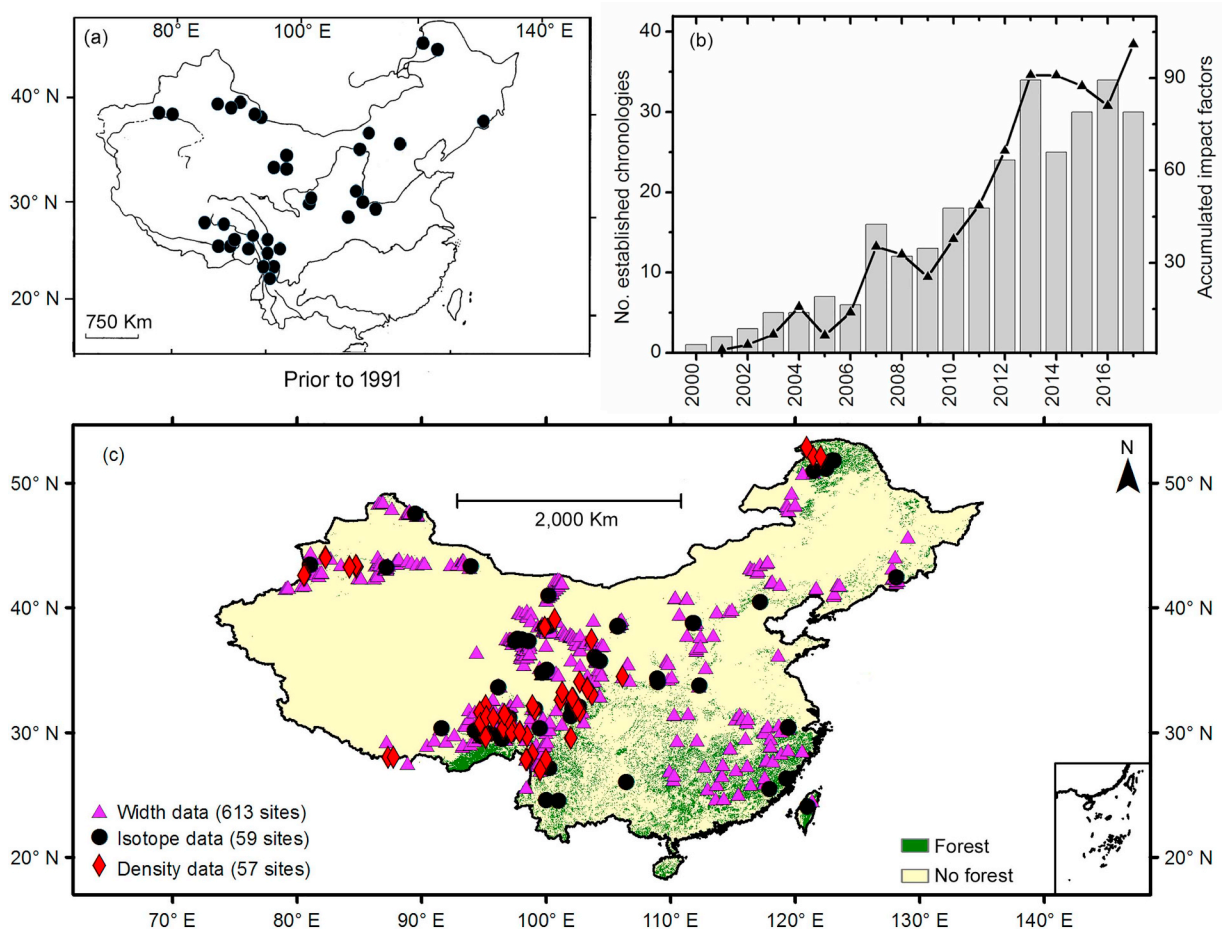

Fig. 1. Tree-ring sampling sites prior to 1991 (a; from Wu and Zhan, 1991), number of published tree-ring chronologies (gray histograms; in total 290 chronologies) and accumulated impact factor in Thomson Reuters Web of Science of the published articles (black line with triangles) during the period 2000–2017 (b), and spatial distribution of sampling sites studied after 2000 with different tree-ring parameters (c). Notably, tree-ring width was probably studied in all cases, also for isotope and density sites. Forest cover data were provided by the Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China (Ran et al., 2012; http://westdc.westgis.ac.cn).

chronology of *Rhododendron aganniphum* var. *schizopeplum* was established for the southeastern TP (Lu et al., 2015), and ring widths of the above tree-line shrub *Rhododendron* were used for the reconstruction of minimum winter temperatures in southwestern China in Sichuan and Yunnan Provinces (Bi et al., 2017). These initial studies have demonstrated the high potential of shrubs for dendroclimatological research in China.

3.2. Tree-ring parameters

Tree-ring width is the most commonly used tree-ring parameter, accounting for 73% of all reviewed chronologies from China (Fig. 1c). Tree-ring width is a simple measure of the radial increment of a tree, and this parameter has contributed to the largest proportion of dendroclimatological research in China, and more generally, worldwide. In addition, intra-annual analyses of the early- or late-wood width have been conducted (Liu et al., 2004a; Chen et al., 2011, 2013; Zhao et al., 2017), potentially providing proxy records within one growing season. For example, a *Pinus tabulaeformis* earlywood width chronology was used to reconstruct precipitation for the period 1691–2006 CE in north-central China (Chen et al., 2012a). This technique is more suitable for specific tree species with a sharp anatomical transition from earlywood to latewood, which usually appears as an obvious color change within the annual ring (Stahle et al., 2009; Björklund et al., 2017).

From an ecological perspective, stable isotope variations in trees hold particular information of climate or environmental changes (McCarroll and Loader, 2004; Young et al., 2012; Loader et al., 2013; Gessler et al., 2014; Hafner et al., 2014). Tree-ring isotope data are also useful where sample replication is limited (Leavitt, 2010). Stable isotopes can potentially reveal a greater proportion of the low-frequency climate signal than tree-ring width series and without the need of traditional detrending techniques (Gagen et al., 2011), although some studies have shown that isotopic data might need detrending too (e.g., Treydte et al., 2006; Esper et al., 2010; Kress et al., 2014). Tree-ring isotope chronologies have been established at a number of sites from different environments in China (Fig. 1c). The most frequently studied isotope ratios are stable oxygen ($\delta^{18}O$, accounting for 13% of all the reviewed dendrochronological records) and carbon ($\delta^{13}C$, accounting for 7%) isotope records. Intra-annual stable isotope variations have been studied in recent years in China (e.g., Fu et al., 2017; Zeng et al., 2017). Due to the time and cost required for sample preparation together with the complexity of the physiological and biochemical processes, the variability of hydrogen isotope ratios (δD) in tree rings has only rarely been studied up to now (Aucour et al., 2002; An et al., 2014; Liu et al., 2015). Nitrogen isotope ratios ($\delta^{15}N$) in tree-rings have only been analyzed in *Populus cathayana* from northwestern China (Zeng et al., 2014).

Maximum latewood density (MXD) is a tree-ring parameter containing a stronger climate or environmental signal than ring width (Schweingruber et al., 1988; Melvin et al., 2013; Esper et al., 2014, 2016, 2018; Matskovsky and Helama, 2014). The earliest MXD chronology covering the period 1600–1988 CE in China was published in

1994 (Hughes et al., 1994). Thereafter, numerous MXD chronologies have been produced, especially for the eastern TP (Fig. 1c; Bräuning and Mantwill, 2004; Fan et al., 2009; Wang et al., 2010; Duan and Zhang, 2014). In addition to MXD, also mean earlywood (Chen et al., 2014; Chen and Yuan, 2014) and latewood (Yu et al., 2013) density chronologies have been developed. At present, approximately 7% of the available dendrochronological records in China are obtained from measurements of tree-ring density.

Wood anatomical parameters, such as cell wall thickness, tracheid radial diameter and microfibril angle (the angle of fibers in the cell wall) have been used to produce climate records for the Arctic (Szymczak et al., 2014; Büntgen et al., 2015, 2018b) and the western Mediterranean Basin (Lehejček et al., 2017). Related physiological research provided explanations as to why wood anatomical properties appear more sensitive to climate than tree-ring width (Drew et al., 2013). However, for China, such studies are still extremely rare to date. Inter-annual variations in the microfibril angle and tracheid radial diameter were measured on *Picea crassifolia* trees on the northeastern TP (Xu et al., 2015b), revealing negative and positive correlations with temperature and precipitation, respectively. These results indicate that there is a great potential also in China to use wood anatomical features to reconstruct climate in sites traditionally considered unsuitable for dendroclimatological studies. If wood anatomical properties exhibit similar climate sensitivity in other regions or species where tree-ring width chronologies do not show climate sensitivity, climate reconstructions from a much wider geographical and climatological range may become possible in the future.

3.3. Chronology length and detrending methods

The longest tree-ring width chronology in China to date originates from the northeastern TP and extends back to 2637 BCE (before Common Era) (Yang et al., 2014a). Chronologies longer than two millennia were previously established in this region (Zhang et al., 2003; Sheppard et al., 2004; Liu et al., 2009; Shao et al., 2010). These longest chronologies (> 2000 years) include subfossil, archaeological, and living trees, while all other chronologies from China (except these multi-millennial ones) were collected from living or dead trees alone (Supplementary Material). Chronologies longer than 600 years of *Juniperus*, *Larix* and *Picea* are mainly available on the TP (Fig. 2a). In the eastern parts of China, most of the tree-ring series are not longer than 400 years. The longest published chronologies from the eastern parts of mainland China are 654 years (1359–2012 CE) from Huashan (Chen et al., 2016) and 657 years (1357–2013 CE) from the southern Taihang Mountains (Zhang et al., 2017b). In Taiwan, the longest chronology (1190–2007 CE) is a tree-ring $\delta^{18}O$ series sampled from an elevation of 2000–2200 m above sea level (a.s.l.) (Liu et al., 2017b).

To preserve the low-frequency climate variations contained in multi-centennial chronologies, especially in those chronologies composed of living and archaeological or dead trees, the biological age trend potentially contained in raw tree-ring data has to be removed without at the same time removing climate-related variability in the derived indexed time-series. Ninety percent of the reviewed tree-ring width chronologies were detrended using traditional exponential functions, linear regression lines, or cubic splines (Fritts, 1976; Cook and Peters, 1981; Cook and Kairiukstis, 1990), which limit the amount of preserved low-frequency information. The Regional Curve Standardization (RCS) approach has been introduced and used to overcome the frequency limitation of traditional curve-fitting standardization (Cook et al., 1995; Esper et al., 2003). However, only approximately 4% of the assessed chronologies were fitted by this method, probably a result of the critical sample depth demand or potential problems associated with RCS (Melvin et al., 2013), e.g., the fitted curves from this method may be distorted by the climate signals and thus result in biased chronology indices (Melvin and Briffa, 2008, 2014). Alternatively, this so-called "trend distortion problem" can be mitigated by employing a "signal free" detrending method (Melvin and Briffa, 2014). This method also reduces the requirement for a large or even temporal distribution of trees. Currently, approximately 5% of all the assessed chronologies have been detrended by using this signal free RCS approach.

To date, a very limited number of studies have specifically tested to improve such detrending methods in China. The performance of the Hugershoff curve (Bräker, 1981) for fitting biological growth trends has been tested and modified with different starting years of tree-ring width chronologies (Fang et al., 2010). The ensemble empirical mode decomposition method was recommended as a candidate detrending approach in tree-ring chronology development (Shi et al., 2012a; Zhang and Chen, 2017). A series of studies associated with the eigen analysis of tree-ring records has been introduced (Yang et al., 2011, 2012a, 2012b; Datsenko et al., 2016). This eigenvalue-based technique was recently applied to establish a chronology covering the period 2627 BCE up to 2012 CE (Yang et al., 2017a). The results indicated that this approach was capable of extracting tree growth variations that did not depend on tree age and micro-environmental conditions of tree stands. However, this technique is restricted to the standardization of very large sample depths.

3.4. Characteristics of the chronologies

As a basic assessment of dendrochronological characteristics and chronology-inherent signals, the mean sensitivity and mean correlation between individual tree-ring series averaged in a chronology (Rbar) are 0.12–0.57 and 0.13–0.80, respectively (Supplementary Material and Fig. 2b, c). Values of the mean sensitivity lower than 0.20 account for 26%, while 72% of the available data range between 0.20 and 0.50. Almost half (48%) of the Rbar values are between 0.30 and 0.50, and the other 26% of values range between 0.50 and 0.70. In total, no clear spatial pattern for the two parameters emerges over China. Thus, latitude or longitude does not systematically influence the prominent variability of mean sensitivity and Rbar, although differences in tree species, site conditions, and elevation can influence these two parameters. Nevertheless, there is a tendency of higher values of the two parameters on the northeastern TP (Fig. 2b, c), indicating that tree-ring width varies substantially from year to year and that the climate (or other environmental factors) may have a relatively stronger influence on tree growth there. The correlation coefficients between tree-ring chronologies and climate data can exceed 0.7 in this region (Fig. 2d).

3.5. Dendroclimatological reconstructions

A large proportion of the published tree-ring chronologies have been used for reconstructing past climate variability. During the reconstruction procedure, statistical calibration equations are established between tree-ring chronologies and available climate data. In China, the beginning of the calibration period (depending on the local available meteorological station data and the coverage of gridded climate products) varies between 1916 and 1972, and 86% of calibration periods start between 1950 and 1960. The length of the calibration period is only 48 ± 7 years (mean ± standard deviation), with the first and third quartiles being 43 and 54 years, respectively. Hence, calibration periods in China are generally very short, making dendroclimatology much more challenging in this country.

3.5.1. Response of tree-ring chronologies to climate or environmental data

By analyzing tree-ring width-based temperature reconstructions, we found that approximately 67% of the records showed significant positive relationships with the current February temperature ($p < .05$; Fig. 3a). More than 50% of the series showed significant positive correlations with July, June, April and March temperatures (in decreasing order). This indicates that the temperature during the growing (April to September) or the previous winter (from the previous October to current March) season significantly influences radial tree growth in China.

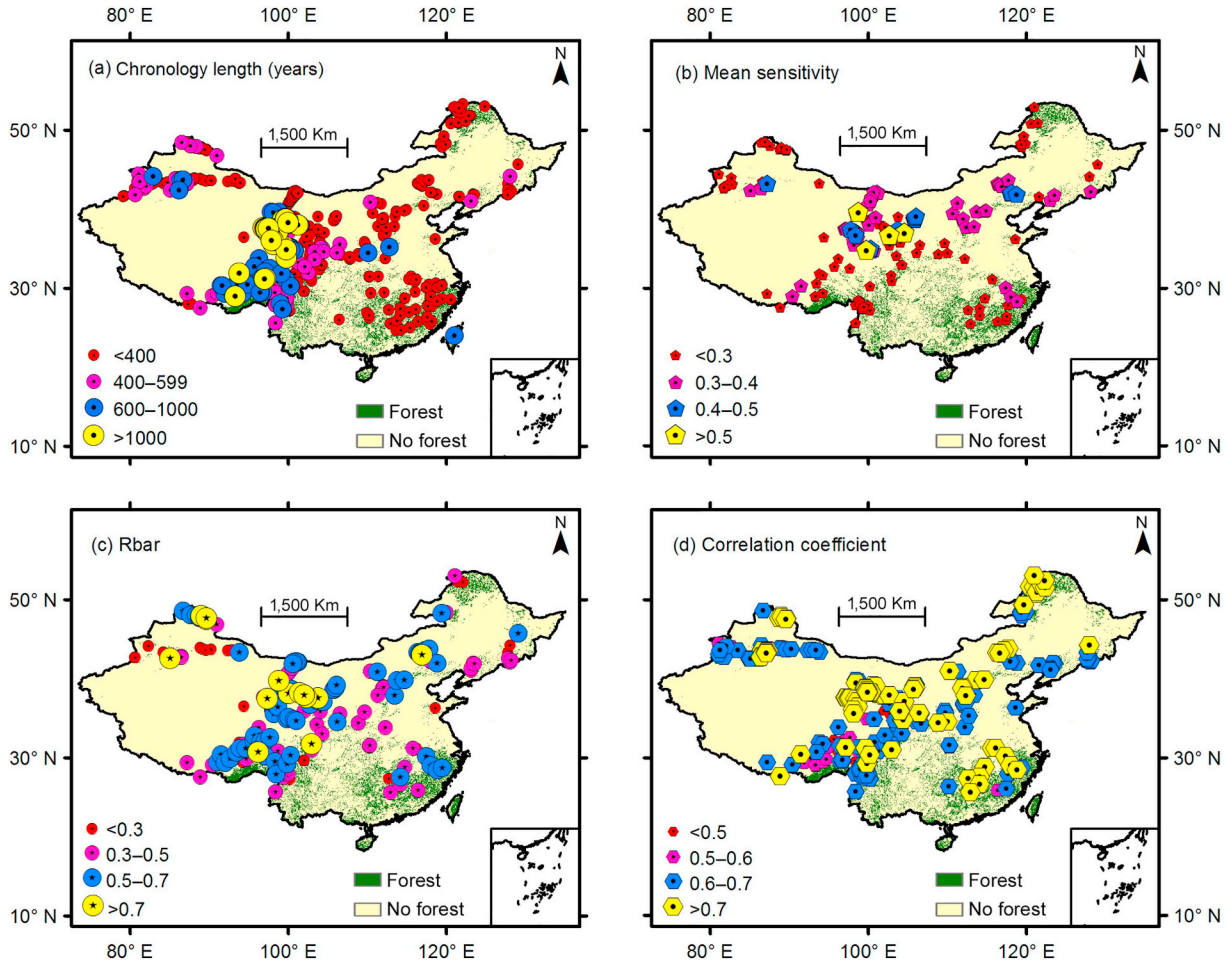

Fig. 2. Characteristics of the dendrochronological records for China published during 2000–2017. (a) Chronology length; (b) mean sensitivity; (c) average correlation coefficient between trees (Rbar); (d) correlation coefficient between tree-ring chronology and climate data during the calibration period. Forest cover data were provided by the Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China (Ran et al., 2012; http://westdc.westgis.ac.cn).

According to these relationships, the reconstructed temperature series for the growing season, winter season, and annual mean accounted for 55%, 18% and 27%, respectively (Fig. 3b). Notably, reconstructions based on significant ($p < .05$) negative correlations between tree-ring width data and temperatures were not included in the abovementioned statistical results. Analyses on the spatial distribution of tree-ring width-based temperature reconstructions show a concentration on the eastern TP (Fig. 4a, b). Growing season or annual mean temperature is generally reconstructed in regions where the mean annual temperature is below 8 °C (or the mean growing season temperature is below 20 °C; data not shown). In addition, some temperature reconstructions were conducted in the sub-tropical parts of China, where the mean annual temperature ranges between 14 and 20 °C (Fig. S1). In this area, tree growth relationships with climate data reveal that tree-ring width is a useful indicator of winter–spring temperature variability (Chen et al., 2012b; Duan et al., 2012; Cai et al., 2016). Higher winter–spring temperatures might protect the root system from chilling damage, and may extend the growing season length by advancing the beginning of cambial activity. Both effects are beneficial for the formation of wider tree-ring width. In the other regions of China, temperature reconstructions are more sporadically distributed (Fig. 4a, b).

The annual precipitation distribution in China shows a strong gradient from humid to arid from southeast to northwest. Most hydroclimate reconstructions were derived from regions where the mean annual precipitation (January–December) is below 800 mm (Fig. S1). The highest proportions of the correlations between tree-ring width and precipitation data occurred in the current May, June and previous August (Fig. 3c). Annual precipitation reconstructions represent 74% of all records (Fig. 3d), wherein the annual precipitation was mostly calculated from the previous July to the current June or the previous August to the current July. Stronger relationships are observed with drought indices from the previous October to the current August (Fig. 3e), because more than half of the tree-ring width data (58%–94%) reach the significance level of $p < .05$ during this seasonal window of the year. The drought indices include the Palmer Drought Severity Index (PDSI; Dai et al., 2004), self-calibrated PDSI (Wells et al., 2004; van der Schrier et al., 2013) and Standardized Precipitation Evaporation Index (Vicente-Serrano et al., 2010). However, the highest correlations with drought indices are found for the growing season period from April to September, and 76% of the available drought reconstructions cover this period (Fig. 3f).

Tree-ring width-based temperature and hydroclimate reconstructions can be generated within the same study region, e.g., on the southeastern TP (Fig. 4). We consider that tree species and site-specific conditions, i.e., elevations of the sampling sites, may result in different growth–climate responses. In particular, from a dendroecological point of view, it is empirically confirmed that tree-ring widths at higher elevation sites are mainly controlled by temperature, while sites at lower elevations are mainly limited by precipitation, or by an interaction between temperature and precipitation, as also shown for other parts of the world (e.g., Babst et al., 2013; St. George, 2014; Hellmann et al., 2016; Klesse et al., 2018). Consistently, the mean elevation of

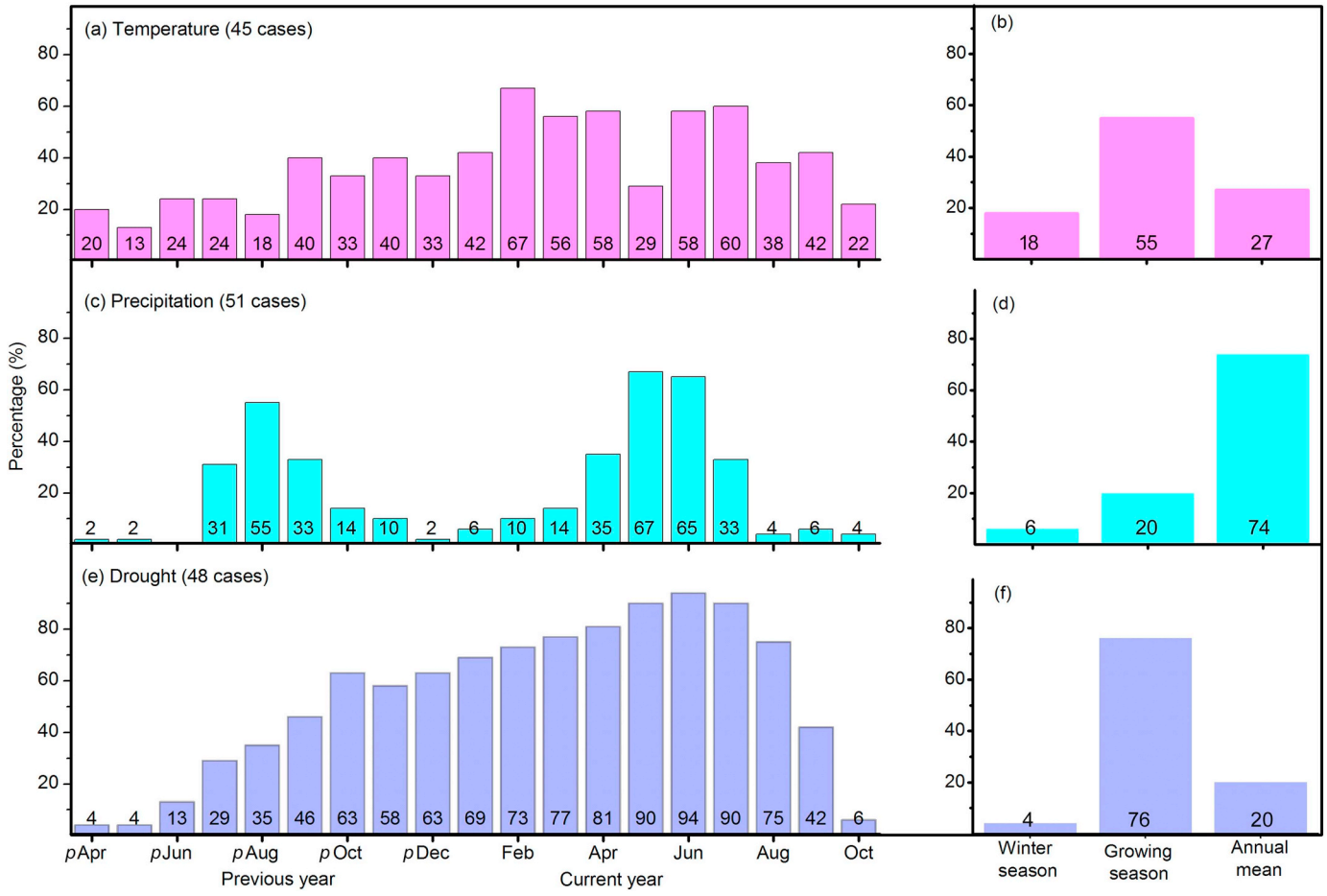
(a) Temperature (45 cases)
(b)
(c) Precipitation (51 cases)
(d)
(e) Drought (48 cases)
(f)
Percentage (%)
20 13 24 24 18 40 33 40 33 42 67 56 58 29 58 60 38 42 22
18 55 27
2 2 31 55 33 14 10 2 6 10 14 35 67 65 33 4 6 4
6 20 74
4 4 13 29 35 46 63 58 63 69 73 77 81 90 94 90 75 42 6
4 76 20
pApr pJun pAug pOct pDec Feb Apr Jun Aug Oct
Previous year
Current year
Winter season
Growing season
Annual mean

Fig. 3. Percentages of significant correlations between tree-ring width chronologies and climate or environmental data from the previous April to the current October ($p < .05$; left panel: a, c, e). The right panel (b, d, f) shows percentages of reconstructed climate series for different annual or seasonal assembles. Drought indices in (e) and (f) include the Palmer Drought Severity Index (PDSI), self-calibrated PDSI and Standardized Precipitation Evaporation Index (SPEI). The prefix *p* indicates months of the previous year. The winter season means the period from the previous October to the current March; the growing season is calculated from the current April to September.

temperature reconstruction sites in China is 3147 m a.s.l. In contrast, the mean elevation for sites reconstructing hydroclimate is 2587 m a.s.l. The 75th percentiles for the two respective elevations are 4098 and 3359 m a.s.l., while the 25th percentiles are 1824 and 480 m a.s.l., respectively.

Tree-ring $\delta^{18}O$ records were consistently found to contain a robust hydroclimate signal on both southeastern (Liu et al., 2014a; Grießinger et al., 2017; Wernicke et al., 2017a; Zeng et al., 2017) and northeastern (Xu et al., 2011; Qin et al., 2015) TP. Such time-series are also available for the sub-tropical (Xu et al., 2013, 2016), the arid northwestern (Liu et al., 2008; Xu et al., 2015a), and the temperate northeastern (Liu et al., 2017a) parts of China. A tree-ring $\delta^{18}O$ series from *Chamaecyparis formosensis* was identified as a sensitive indicator of both regional hydroclimate and sea-surface temperatures (SSTs) in the Taiwan Province, China (Liu et al., 2017b). Compared to tree-ring $\delta^{18}O$ series, however, inconsistent climate signals of tree-ring $\delta^{13}C$ records were reported from different study regions. Considering that $\delta^{13}C$ in the wood represents the interplay between stomatal conductance and photosynthetic rate, it can reflect either variations in soil moisture, sunlight, or the concentration of CO_2 in the atmosphere (McCarroll and Loader, 2004; Anchukaitis, 2017). For example, $\delta^{13}C$ was identified to be a suitable proxy of site-related physiological responses to the local environment on the southeastern TP (Zeng et al., 2017), e.g., changes of intrinsic water-use efficiency (Fu et al., 2017; Huang et al., 2017). On the northeastern TP, tree-ring $\delta^{13}C$ was found to reflect the April–August temperature variability (Wang et al., 2011), although this response was considered non-stable during the past millennium (Wang et al., 2016). A significant correlation was detected between the mean temperatures of May–July and tree-ring $\delta^{13}C$ data in Nanwutai, north-central China (Liu et al., 2014b). However, seasonal precipitation (February–July) and relative humidity (April–June) were reconstructed based on tree-ring $\delta^{13}C$ series in northwestern (Liu et al., 2004b) and southern (Liu et al., 2017c) China, respectively.

Maximum latewood density (MXD) from trees growing in cool environments in China (e.g., at high-elevation sites) mainly reflect temperature conditions during the latter part of the growing season (Wang et al., 2010; Li et al., 2015; Liang et al., 2016), which is related to the physiological processes of cell wall thickening and lignification of latewood tracheids (Fritts, 1976; Schweingruber, 1988; Rossi et al., 2016).

3.5.2. Temperature reconstructions

The parameters used for temperature reconstructions are tree-ring width, MXD and $\delta^{13}C$ records (in total 68 series). Mean, minimum and maximum temperatures were reconstructed over various multi-month seasons or a full-year scale. Most temperature reconstructions are based on individual site or local-scale chronologies. For example, using traditional linear regression functions, Wang et al. (2014) developed a mean annual temperature reconstruction covering the period 984–2009 CE for Qamdo County, southeastern TP. A reconstruction of the maximum temperature during the season March–October revealed a slow cooling trend from 1806 CE to 1980, followed by a rapid warming trend

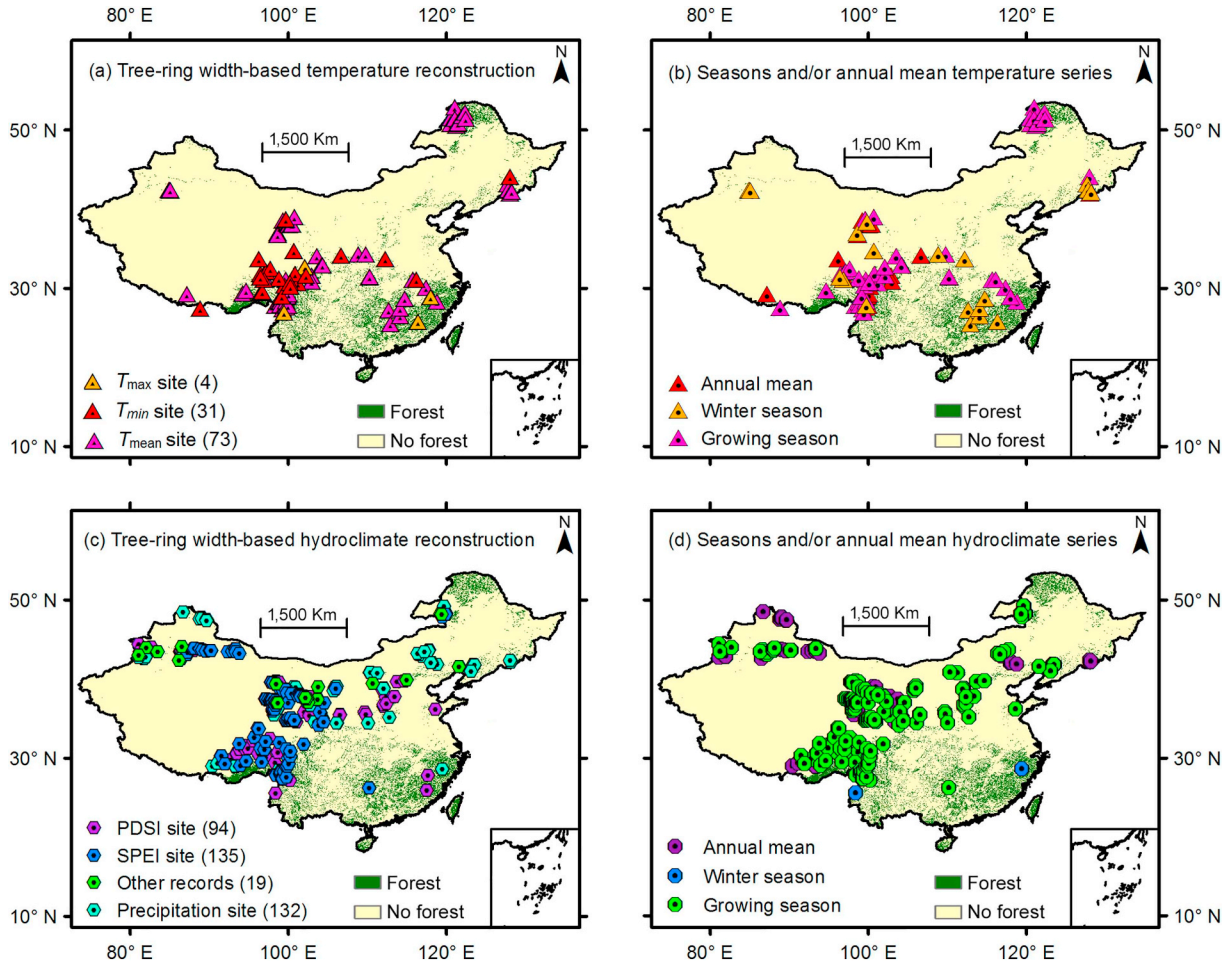

Fig. 4. Tree-ring width-based temperature (a, b) and hydroclimate (c, d) reconstructions. Reconstructions based on significant negative correlations between tree-ring width data and temperature are not shown. T_{max}, T_{min} and T_{mean} in (a) denote maximum, minimum and mean temperatures, respectively. Other drought series in (c) represent relative humidity reconstructions or dry/wet indices. The data in the brackets are the respective total numbers of the sampling sites. Forest cover data were provided by the Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China (Ran et al., 2012; http://westdc.westgis.ac.cn).

in the Sanqingshan Mountains, southeastern China (Cai and Liu, 2017).

Several regional-scale temperature reconstructions are currently available on the TP. Late summer (August and September) temperature was reconstructed from a network of 22 MXD chronologies on the southern TP (Bräuning and Mantwill, 2004). Based on seven alpine treeline locations across the southeastern TP, Shi et al. (2015a) reconstructed regional summer (June–August) minimum temperatures for the period 1820–2009 CE. The study showed that extreme warm and cold events (defined as years exceeding 1.5 standard deviations above or below the 30-year filtered trend) were more frequent since 1950 CE and the post-1990 period was the warmest of the last 200 years. By using a nested composite-plus-scale approach, Wang et al. (2015) combined 12 tree-ring width chronologies for the common period 1000–2005 CE and showed that warm episodes occurred during large parts of the sixteenth, nineteenth, and twentieth centuries, whereas cold episodes persisted during the eleventh, seventeenth, and eighteenth centuries. Wang et al. (2015) prolonged the previously available two summer temperature reconstructions (Bräuning and Mantwill, 2004; Shi et al., 2015a) to the full past millennium and spatially extended the network to the northeastern TP. Significant relationships with the Atlantic Multidecadal Oscillation/Atlantic Multidecadal Variability (Wang et al., 2017) were considered the driving force of the reconstructed temperature variability on the TP. In addition, reconstruction uncertainties were added to Shi et al. (2015a) and Wang et al. (2015), and therefore resulted in improved temperature estimates on the TP.

In the subtropical parts of China, regional-scale temperature variability has also been reconstructed through a tree-ring network consisting of 31 sampling sites (Duan et al., 2013). This study assessed the characteristics of temperature extremes during the winter months (January–March) over the period 1825–2008 CE. It was found that, despite global warming, subtropical China has frequently experienced periods of depressed winter temperatures since the 1930s. Cold and warm phases corresponded with the varying strength of the Siberian high; hence, this study provided insights into the potential linkages between high- and low-latitude climate systems. In contrast to the previous studies that used traditional linear relationships to extract climate signals from tree-ring chronologies in the subtropical parts of China (Duan et al., 2012; Shi et al., 2013), this study by Duan et al. (2013) applied a new method by examining the percentage of trees in each year that showed “abnormal” growth reductions. Time series of tree percentage might be a good indicator of climatic change in such wet and humid regions. Although the long-term availability of old trees suitable for climatic studies are limited in sub-tropical China, reconstructed data extending over a couple of centuries will be valuable to prolong the existing instrumental records that mostly cover the last half century (Cao et al., 2013).

One promising approach is based on Bayesian model averaging (Zhang et al., 2016b). This technique weights the tree-ring chronologies according to their contributions to the actual climate signals and thus

has an advantage in integrating chronologies to reconstruct regional mean temperature. Bayesian approaches are probabilistic and yield improved uncertainty estimates. As a case study, regional mean temperature was reconstructed for the period 1628–2005 CE on the Yunnan–Guizhou Plateau, southwestern China (Zhang et al., 2016b). A high correlation between reconstructed and observed temperatures was achieved during the calibration period 1961–2005, suggesting that the model captured suitably the regional changes in temperature. A larger use of this method is expected to extend its application in dendroclimatological research.

Multi-proxy temperature reconstructions derived from different natural archives including tree-rings, ice cores, lake sediments and historical documentary data for China over the past two millennia were first presented by Yang et al. (2002). Using nine proxy records, Yang et al. (2002) identified three prominent climate phases, including the *Medieval Warm Period* (a.k.a. Medieval Climate Anomaly, here, c. 800–1100 CE), the *Little Ice Age* (here, c. 1400–1850 CE), and the recent warming phase since 1850 for China, thus allowing the long-term evolution of temperature in China to be placed in a larger hemispheric and global context. Thereafter, several reconstructions based on a larger number of proxy records were conducted and regional differences in temperature change across China were revealed (Wang et al., 2007; Ge et al., 2010, 2013, 2017). In particular, reconstruction uncertainties were stressed by Ge et al. (2010, 2013, 2017). Warming rates, amplitudes, and periodicities of temperature change in China were systematically assessed in a recent study (Ge et al., 2017), which detected that late twentieth century temperature levels in China may not be unprecedented for the past two millennia, although the most rapid rate of warming occurred at the end of the last century, during 1870–2000 CE (with a rate of 0.56 °C ± 0.42 °C per 100 years) in accordance with results from the whole Northern Hemisphere (Ljungqvist et al., 2012). The combined spatial patterns of dryness/wetness and temperature in eastern China were demonstrated and thus improved our understanding of past temperature–hydroclimate co-variability in the region (Ge et al., 2017). However, the overall lower resolution of some proxy records in most multi-proxy reconstructions may provide fewer degrees of freedom in the calibration and verification periods and thus increase uncertainty in the final climate reconstruction (Christiansen and Ljungqvist, 2017).

3.5.3. Hydroclimate reconstructions

Quantitative precipitation or drought signals can be extracted from both tree-ring width (83% of available series) and $\delta^{18}O$ data (15% of available series). Like temperature reconstructions, a large part of hydroclimate studies are based on single site studies or studies combining local sites. For example, the May–June PDSI for 1494–2004 CE was reconstructed in the Nagqu region on the south-central TP (Wang et al., 2008). Spring (here, March–May) drought was revealed by three tree species since 1655 CE in the central Hengduan Mountains, southwestern China (Fan et al., 2008). Gou et al. (2015) presented a millennium-long (1009–2010 CE) June–July SPEI reconstruction from the eastern Qilian Mountains, northwestern China.

At a regional scale, the longest tree-ring width-based annual precipitation (from previous July to current June) reconstruction was performed utilizing 17 sampling sites on the northeastern TP (Yang et al., 2014a). The signal free RCS-based reconstruction of Yang et al. (2014a) indicates that the last 10-, 25-, and 50-year periods all appear to be the wettest during the past three and a half millennia. Based on a network of 23 tree-ring width chronologies from the eastern TP, Zhang et al. (2015) investigated the spatial and temporal variability of moisture conditions during the past five and a half centuries. A prominent sign of advancement is the increased number of sampling sites or used tree-ring width chronologies, as well as the increasing spatial coverage, particularly for the southern sub-region (Zhang et al., 2015). The method of chronology construction used by Yang et al. (2014a) enables the comparison of variations in precipitation totals over long timescales as well as shorter periods during the past three and a half millennia. Hence, both studies promote further regional-scale hydroclimate reconstructions for China.

Regional-scale hydroclimate reconstructions were also conducted in the semi-arid western Chinese Loess Plateau (Fang et al., 2017). By using a frequency-based method, a composite chronology from 401 tree-ring series obtained from eight sites was used to reconstruct annual precipitation from the previous August to the current July for the period 1568–2012 CE. The driest period was identified in the 1920s and 1930s, matching the regional droughts recorded in historical documentary data (Fang et al., 2017). Consistent drought variability on decadal to centennial timescales was identified in the western (the Qilian Mountains and the Hexi Corridor) and eastern (the Great Bend of the Yellow River) parts of the northern fringe of the Asian summer monsoon region in China (Yang et al., 2014b). Fang et al. (2017) were able to show that linkages between drought variation on the western Chinese Loess Plateau and western North America were likely related to the Interdecadal Pacific Oscillation. Large scale analyses of drought variability and their possible driving mechanisms may be regarded as one of the major advances made in dendroclimatological research for China.

Since tree-ring width integrates the seasonal moisture balance in a similar way than ecosystems and watersheds (Anchukaitis, 2017), tree-ring records can also serve as surrogates for river discharge (Yuan et al., 2007; Gou et al., 2010; Qin et al., 2010; Yang et al., 2012c) and glacier mass balances in specific environments (Bräuning, 2006; Xu et al., 2012; Zhu et al., 2013; Hochreuther et al., 2015). For instance, tree-ring width chronologies from six sites were developed to provide estimates of Yellow River streamflow for the period 1409–2001 CE (Gou et al., 2007). The results indicated that Yellow River streamflow has decreased significantly since the 1980s, but were not yet out of the range of earlier streamflow fluctuations over the past six centuries. Based on the approach of artificial neural networks, streamflow was reconstructed for the northern slopes of the Tianshan Mountains, northern China (Yang et al., 2017c). A consistent maximum glacier extent ending in approximately 1740–1780 CE was reflected by tree-ring records on the southeastern TP (Bräuning et al., 2016). Those studies clearly demonstrate the applicability of tree-ring data for understanding variations in hydrological conditions and atmospheric circulation patterns which are connected to terrestrial ecosystem processes.

3.5.4. Field reconstructions

A limited number of climate field reconstructions have been developed for China based on tree-ring data. Here, a field reconstruction refers to large spatial scale reconstructions for the whole China or across the Asian continent, with datasets used mostly or entirely from tree-ring chronologies. The first version of the Monsoon Asia Drought Atlas (MADA) over the past 700 years (1300–2005 CE) was derived from a network of 327 tree-ring chronologies (Cook et al., 2010). However, as already noted, the spatial distribution of tree-ring sites over China is inhomogeneous, and vast areas remain missing in the MADA dataset. In total, 88 single study sites were included, with 73% and 17% located on the eastern TP and in northwestern China, respectively. Thus, the estimations may be geographically biased to some extent. Nevertheless, this work represents an important step forward, and the MADA provides valuable information to study the spatio-temporal fingerprint and magnitudes of reconstructed monsoon failures over the past seven centuries.

Summer (June–August) temperatures for temperate East Asia were reconstructed based on a network of 422 annual tree-ring chronologies covering the period 800–1989 CE (Cook et al., 2013). The point-by-point regression-based reconstruction indicated a moderately warm medieval period (~850–1050 CE), generally cooler conditions (~1350–1880 CE) and the twentieth century warming. The timings of cold and warm periods are generally consistent with Yang et al. (2002)

and other multi-proxy reconstructions for China, although with somewhat different starting and ending years of the various cold and warm periods. The different proxy types and differences in their spatial coverages probably resulted in some bias; differences in reconstruction methodologies may also play a role (Christiansen and Ljungqvist, 2017). The influence of volcanic forcing on the East Asia summer temperatures was evidenced by Cook et al. (2013). The application of various tests of reconstruction quality is another improved characteristic of this study. However, substantial uncertainties still remained in the reconstructed series, particularly for low-frequency changes. It may be noted that nearly 77% of the tree-ring chronologies used in this study of temperature reconstruction were previously identified as containing a hydroclimate signal over monsoon Asia (Cook et al., 2010). Hence, some caution should be taken in interpreting any joint features of the two reconstructions.

A millennium-long multi-proxy gridded field reconstruction of annual temperature for China was conducted by applying a point-by-point regression method combined with composite-plus-scale and regularized errors-in-variables approaches (Shi et al., 2012b). Overall, a network of 415 climatic proxy series was used, and 89.9% were tree-ring records. The results showed that the late twentieth century was likely the warmest period over the past millennium in China (Shi et al., 2012b), contrary to the results obtained by Ge et al. (2010, 2013, 2017). However, the temperature change in the eastern and western regions of China was not synchronous during much of the past millennium. Low reconstruction skill is revealed by un-passed validation tests for some grid points, which may be the result of a low resolution and regional representation of the selected proxy data. The Asian summer temperature over the past millennium was reconstructed by using various types of proxy records (Shi et al., 2015b), in which tree-ring series account for > 93% of the input data (418 proxy series in total). Compared to the reconstruction by Cook et al. (2013), the reconstruction by Shi et al. (2015b) contained somewhat more low-frequency variability. One limitation of this multi-proxy reconstruction was the low reconstruction skill in some grid points because of an insufficient number of proxy records, particularly prior to approximately 1400 CE. Hence, improvement of field temperature reconstructions relies on more evenly distributed proxy data in time and space as well as an overall higher temperature signal in the input proxy data (see Christiansen and Ljungqvist, 2017 for further discussions). A comparison of this reconstruction with seven climate model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) in Shi et al. (2015b) provided an example of how to investigate the influence of external forcings (e.g., solar activity, volcanic eruptions and greenhouse gases) on temperature change.

A multi-proxy-based field precipitation reconstruction was conducted using the Regularized Expectation Maximization (RegEM) method extending back to 1470 CE over the Asian continent (Feng et al., 2013). In total, 207 proxy series were used, and 49% (101 records) of them were from tree-ring based hydroclimate reconstructions. Statistical verification revealed that this reconstruction was skillful over humid climate areas, but not in semiarid and arid regions. This reconstruction provides a larger context for understanding the spatial scale, severity, and societal impacts of droughts. However, compared to the principal component analysis, the over-dependence of the RegEM technique on the instrumental target may lead to noticeable bias in the reconstruction (Schneider, 2001; Christiansen et al., 2009; Christiansen, 2011).

3.5.5. Large spatial scale sea surface temperature reconstructions

Large spatial scale sea surface temperatures may influence weather around the world and climate through far-reaching patterns known as atmospheric teleconnections (Deser et al., 2010; Chylek et al., 2014; Seim et al., 2018). Tree-ring series from some specific environments can be used to reconstruct sea surface temperatures to improve our understanding of their temporal and spatial in a long-term context (D'Arrigo et al., 2005; Wilson et al., 2010; Li et al., 2011). On the one hand, numerous dendroclimatic records have been linked to the teleconnections in different climate zones of China (e.g., studies conducted by Peng and Liu, 2013; Bao et al., 2014; Cai et al., 2015; Zhang et al., 2017b). On the other, efforts have been undertaken by Chinese dendroclimatologists to directly reconstruct sea surface temperatures from tree-ring records. For example, Li et al. (2013a) presented a seven-century-long (1301–2005 CE) El Niño/Southern Oscillation (ENSO) reconstruction based on 2222 tree-ring chronologies from both the tropics and the mid-latitudes. Liu et al. (2017b) reconstructed annually resolved Niño 4 (located in the heart of the central Pacific ENSO region) SSTs for the past eight centuries, showing relatively high SSTs during the late twentieth century probably related to anthropogenic global warming. Such studies allow the evaluation of the oscillatory nature of atmospheric circulation patterns and provide crucial constraints for improving climate modeling results as well as their future projections.

3.6. New monitoring and modeling approaches associated with dendroclimatology in China

Significant progress in tree growth–climate associated monitoring work has been achieved on a global scale by using microcoring or dendrometer data, especially in Europe (e.g., Camarero et al., 2010; Rossi et al., 2016; Pérez-de-Lis et al., 2017). Wood formation, xylem phenology and their relationships with climate or environmental factors have been investigated on daily to monthly time-scales. For China, this is a field that emerged recently. Preliminary but substantial advancement has been achieved in the most recent years (Fig. 5; Liang et al., 2009; Wang et al., 2012; Li et al., 2013b; Xiao et al., 2014; Ren et al., 2015, 2017; Zeng et al., 2018). For example, Li et al. (2017) examined weekly xylogenesis in two natural *Abies georgei* tree-line sites on the southeastern TP. Zhang et al. (2017a) found that short-term nitrogen deposition was unable to influence the timing and dynamics of xylem formation in *Pinus massoniana* in central China. Such studies provide a broad knowledge base about the processes controlling tree cell production, which determine the characteristics of the produced cells and thus are important for setting up tree growth–climate relationships on a finer time-scale. However, data series based on monitoring field work are often of limited length of only a few years of direct observations, which can result in statistical instability of the obtained growth models due to low number of degrees of freedom and the possible lack of extreme climatic conditions experienced during the short study periods.

Process-based models have been used for several decades in dendroclimatology (Le Roux et al., 2001; Guiot et al., 2014; Babst et al., 2018). According to the main physiological processes considered in the different models, the causal biological relationships between tree-ring data and climate factors can be clearly identified. By using the MAIDEN ecophysiological forest model (Misson, 2004), the positive effect of climate warming on stem growth can be well captured (Gennaretti et al., 2017). Forward (Zeng et al., 2016, 2017) and backward (Wernicke et al., 2017b) models were used to examine the relative importance of environmental controls on tree-ring isotopic data on the TP. The tree-ring process-based Vaganov-Shashkin (VS) model (Fritts et al., 1991; Vaganov et al., 2006) has been widely applied in different study regions across the world (Evans et al., 2006; Anchukaitis et al., 2012; Touchan et al., 2012; Shishov et al., 2016; Popkova et al., 2018). Similar applications are now also available in China (Fig. 5; Shi et al., 2008; Zhang et al., 2011; Zhang et al., 2016a; He et al., 2017). By using the VS-Oscilloscope model (Shishov et al., 2016), a new perspective on vegetation phenology shifts during the period 1960–2014 was revealed for the TP (Yang et al., 2017b). The use of this novel tree-ring process-based model that converts daily weather station data into indices of the start and end of the growing season represents a major advance in the emerging field of phenoclimatology. Scaling up this analysis would provide additional information on phenological responses of terrestrial

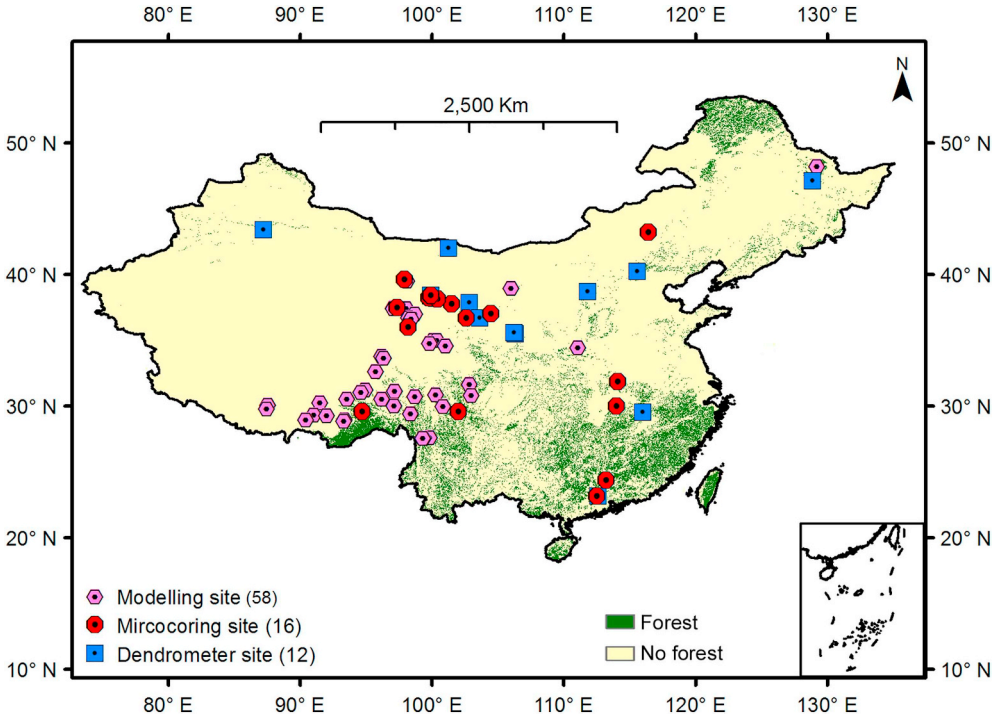

Fig. 5. Monitored (microcoring and dendrometer approaches) and modeling sites associated with dendroclimatology in China. The data in the brackets are the respective total numbers of the studied sites. Forest cover data were provided by the Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China (Ran et al., 2012; http://westdc.westgis.ac.cn).

ecosystems to ongoing climate change (e.g., the study conducted by He et al., 2018). Herein, we stress the usage of models because they allow quantification of combined influences of climate or environmental factors on the growth increment, or the isotopic composition of trees on the daily time-scale and can deepen our understanding of the tree physiological processes underlying statistical correlations between tree-ring parameters and climate variables. Furthermore, models can also test whether the observed variability in tree growth–climate relationships arises as a function of climate itself, or through possibly unobserved influences by environmental or ecological changes, e.g., increased atmospheric CO_2 concentrations (Boucher et al., 2014). Apart from the traditional dendroclimatological studies that often simply rely upon linear transfer functions, studies considering the non-linearity of the process involved in the transformation of climate variability into tree growth are needed, especially in the context of the ongoing climate warming and increase in CO_2 concentrations.

4. Conclusions and outlook

Significant progress in dendroclimatological research in China has been achieved during the period 2000–2017. Sampling sites have been expanded over almost the entire naturally forested regions of China. Additional coniferous and broadleaf trees (i.e., *Populus euphratica*) as well as shrub species have been studied by application of traditional dendrochronological approaches. These advances have created opportunities for a wide range of detailed local-to-regional climatological and ecological studies (e.g., Yang et al., 2014a; Zhang et al., 2015; Liang et al., 2016; Liu et al., 2017b, 2018). An expanded spatial distribution, especially in high-elevation and subtropical areas, and higher site density of tree-ring data provide opportunities to study past climate change and its links to large-scale climate patterns, e.g., the El Niño/Southern Oscillation, the East Asian monsoon, and the Atlantic Multidecadal Oscillation. The recently introduced different climate reconstruction methods, including reconstruction uncertainty information, as well as the new fields associated with monitoring and modeling work can be regarded as significant progress in dendroclimatology in China. However, the lack of knowledge concerning the complex climate or environmental signals recorded in many tree species still presents a significant methodological challenge. Moreover, most of the reconstruction work is based on single-site or local-scale chronologies, with an almost exclusive focus on tree-ring width as the only studied parameter.

In future studies, composite multiple tree-ring parameters, especially stable isotope and wood anatomical data, are suggested to explore their potential for climate reconstructions. Improvement of applied detrending methods based on the available larger sample depth of tree-ring chronologies becomes increasingly feasible. The inconsistent climate signals extracted from tree-ring carbon isotope data need further investigations.

Integrating or synthesizing the available tree-ring chronologies to reveal regional-scale hydroclimate reconstructions in northwestern China is recommended. Moreover, a better understanding of the relationships between temperature changes and the spatiotemporal patterns of droughts is important under the context of continuous climate warming.

Large spatial scale or field reconstructions are envisaged by employing statistical methods to integrate tree-ring chronologies with other types of paleoclimate proxy data. Moreover, further quantifying the reconstruction uncertainties and refining the estimates of past temperature and hydroclimate change would be an advantage. Combining climate reconstructions with climate model simulations (e.g., the results from the Coupled Model Intercomparison Project Phase 5, CMIP5; Taylor et al., 2012) is also proposed to evaluate the effects of various internal or external climate forcings in different study regions.

Intensified monitoring and modeling work associated with the tree growth process and their relationships with climate or environmental data are expected, but it is recommended to extend the observation periods to include the full range of climatic variability and related tree responses at different study sites. Specifically, monitoring of the tree-radial growth process should be broadly applied on the southeastern Tibetan Plateau and in the sub-tropical region of China, where tree growth–climate relationships are more complex and heterogeneous. Linking dendrochronology with other methods (e.g., remote sensing and tree physiology) will be another way to facilitate the advance of dendroclimatology in China.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earscirev.2019.02.012.

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